



# Sustainability assessment of technologies for resource recovery in two Baltic Sea Region case-studies using multi-criteria analysis

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## ABSTRACT

Sustainability assessments can be a powerful tool in decision-making regarding technical innovations. In this study, a sustainability assessment of technical systems for recovering nutrients and carbon from domestic wastewater is presented. Multi-criteria analysis was used to calculate a sustainability score of three different technical systems compared to a baseline in two case-studies: the Fyriså river catchment in Sweden and the Stupia river catchment in Poland. Two participatory workshops with local stakeholders were held in each case-study, the first to co-develop the system alternatives and sustainability criteria and the second to collect stakeholder weighting of the criteria. Although the systems assessed in both case studies were similar, the resulting sustainability scores were different. In Fyris, although the differences in scores was small, the preferred alternative was introduction of source-separation followed by a large redesign of the treatment and phosphorus extraction from incinerated sludge was the least sustainable alternative. For the Stupia systems the scores varied more, and the preferred system was a large redesign of the wastewater treatment followed by ammonia stripping of the reject water and the source-separation alternative received the lowest score. In both case-studies, the more costly system received highest sustainability score indicating the large potential benefits of enhancing resource recovery from domestic wastewater. Stakeholders did not prioritize technical aspects over the other sustainability criteria, yet most of research on resource recovery interventions is focused on technical performance.

## 1. Introduction

In order to sustain a growing population with food, the resource efficiency in the food system must increase (Manning 2015). Agriculture needs an input of plant nutrients, which today is heavily dependent on non-renewable resources. Phosphorus (P) fertilizers are manufactured using mined phosphate rock and which is listed as a critical raw material by the EU (European Commission 2017). Nitrogen (N) fertilizers is manufactured from ammonia N fixated from the atmosphere, a process which uses natural gas. The production of fertilizers uses about 1.2% of the world primary energy, most of which is associated with production of N fertilizers. This leads to considerable emissions of greenhouse gases, contributing to climate change (Razon 2018). Thus, fertilizer production

needs to be improved in order to ensure a sustainable growth of agricultural capacity.

Reactive N and P contribute to eutrophication. The Baltic Sea is particularly vulnerable to eutrophication due to its large catchment and long renewal time (Fleming-Lehtinen et al., 2015). The contribution of point sources, mostly wastewater treatment plants, to the Baltic Sea in 2014 was 12% of N and 24% of P riverine loads (HELCOM 2018). Preventing eutrophication has been the major driver for managing P in wastes, and although important, it is not enough motivation to achieve a sustainable P cycle (Cordell et al., 2009). Recovering and reusing nutrients is one piece of the puzzle of achieving a sustainable P cycle.

Human excreta is the most nutrient-rich waste stream in urban areas and reuse of this stream is one of the paths towards closing the nutrient

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loops (Cordell et al., 2009). Furthermore, minimizing dilution of waste streams through source separation, like separating toilet waste “black-water” from other domestic wastewater “greywater”, makes nutrient recovery easier as the nutrients are concentrated in smaller volumes (McConville et al., 2015). In recent years, there has been a growing interest in recovery of nutrients in wastewater for reuse (Guest et al., 2009; McConville et al., 2017). Implementing resource recovery in wastewater management can provide multiple benefits to society (Trimmer et al., 2017) and returning carbon- and nutrient-rich sludge to agriculture constitutes a potential carbon sink (Pitombo et al., 2015) as well as potentially increased water holding capacity and yields. A recent systematic mapping of technologies for recovery and/or reuse of nutrients and carbon from domestic wastewater listed 27 different technologies (Johannesdottir et al., 2020). The technologies for recovery most frequently appeared in a constellation with other technologies, for example incineration of sludge followed by extraction of P from the ash. Evaluation of the sustainability of a technology is preferably done on the technological constellation in order to account for the operational function and performance.

Barquet et al. (2020) discuss barriers and opportunities for implementing and upscaling circular solutions for P in the Baltic Sea Region. They highlight the need to look beyond purely technical needs and instead broaden the spectrum of factors involved in hindering or triggering innovation transitions. The exploration of these factors, however, require approaches that can capture both quantitative as well as qualitative data, and which can bring together expert-based assessments with other types of knowledge including stakeholder inputs on perceived benefits and tradeoffs. Involvement of community members and key actors through participatory methodologies are crucial for integrating opinions in the formal decision-making process because of large dependence on the level of acceptance by communities, on whether the solution is institutionally and financially feasible (Barquet and Cumiskey 2018).

Multi-criteria analysis (MCA), also referred to as multi-criteria decision analysis, is a decision-support tool which can integrate aspects from different dimensions in a sustainability assessment. With MCA, quantitative (with different units) and qualitative criteria can be compared and evaluated. MCA is a widely used tool and has been applied in many different sectors including waste management (Achillas et al., 2013). The aim of the MCA method is to solve for the best option, given the performance of the alternatives on a selected group of criteria and prioritization between them (see for example Milutinovic et al. (2014)).

To summarize, there is a great need for implementing more circular solutions and resource recovery in the wastewater sector. When developing decision-support, consideration needs to be taken to several aspects, not only the technical or economical. Technologies need to be assessed for their sustainability in the constellation of technologies and context in which they are intended to be implemented. Local stakeholders play an important part in the local context and can affect whether an innovation will be sustainable or not. In this paper, we present a comparative sustainability assessment of wastewater management systems for recovery and reuse of carbon, N and P facilitated by a participatory MCA. The aim was to compare an aggregated sustainability index of three alternative nutrient recycling wastewater systems in two Baltic Region case studies. It is the authors' belief that the assessment done contributes to decision-making in a useful way, as well as it contributes to research in the field of nutrient recovery from wastewater.

## 2. Methods

The general method for the MCA was based on Malmqvist et al. (2006). The linear, weighted sum method of MCA was chosen because it is straight-forward, transparent and would more easily facilitate the stakeholder's engagement and sense of ownership over the process than a more complex method (examples of which are found in for example Huang et al. (2011)). The basic steps of the analysis and stakeholder

involvement are illustrated in Fig. 1. Two case-study sites were used: the Fyris river catchment area in Sweden and the Stupia river catchment area in Poland. We adopted a whole catchment area perspective in the study and included all wastewater treatment plants within them. This large perspective gives insights on how large an impact the studied technical systems have on the whole area and in effect, on the Baltic Sea. Two participatory workshops were held in each area with local stakeholders. The first workshops aimed at receiving input from local stakeholders on the goal and scope definition, selection of evaluation criteria and selection of alternatives. Local stakeholders from different sectors were invited, including municipality, wastewater treatment, forestry, local environmental interest groups and local consultants. At the second workshop, the main aim was to receive stakeholder weightings of the criteria. This multi-criteria sustainability assessment was performed within the project BONUS RETURN ([www.bonusreturn.eu](http://www.bonusreturn.eu)). This work is also described in a project report (Johannesdottir et al., 2019). Calculation sheets, references and assumptions can be found in Appendix A. Supplementary Data.

### 2.1. Case-study sites

The two case-studies were chosen because they are of similar size and both drain into the Baltic Sea. Both also have the main river flowing through cities of similar sizes and are affected by pollution, such as eutrophication.

#### 2.1.1. Fyris

The Fyris river (*Fyrisån*) basin located in Uppsala county in South-Eastern Sweden, covers an area of 1982 km<sup>2</sup> and belongs to the wider Mälaren-Norrström drainage basin. The Fyris river flows roughly north-south over a distance of approximately 80 km with a 110 m altitude difference and drains into Lake Mälaren which in turn drains into the Baltic Sea (The Fyris River Association 2020). The climate in the basin is classified as Dfb (warm-summer humid continental (Beck et al., 2018)) with an average annual precipitation of 550–600 mm (Swedish Meteorological and Hydrological Institute 2020). The land use is distributed as 60% forests, 32% agriculture, 4% wetlands, 2% lakes and 2% urban area. The city of Uppsala (approx. 170 000 inhabitants) lies in the southernmost part of the basin where also the city waste treatment plant (Kungsängsverket) discharges into the Fyris river. Most stretches of the river are affected by eutrophication, have barriers to fish migration and habitat destruction (Länsstyrelsen Västmanlands län and Vattenmyndigheten Norra Östersjön 2017).

#### 2.1.2. Stupia

The Stupia catchment is a coastal river basin located in Pomerania region, northern Poland. The catchment covers an area of 1,623 km<sup>2</sup> and is drained to the southern Baltic Sea by the 138 km long Stupia river. According to Koppen-Geiger climate classification, it belongs to Dfb class (Warm-summer humid continental (Beck et al., 2018)). The long-term annual rainfall in the area is estimated to be 850 mm. In the last two decades, the land cover has undergone gradual shift resulting in increased urban and forested areas on expense of the agricultural land. In this period the urban area doubled to constitute currently 5% of the catchment area (Polish Chief Inspectorate of Environmental Protection 2018), the agricultural area dropped slightly below 50% and forest reached 44%. Nearly 2% of the catchment is occupied by wetlands. The city of Słupsk, largest in the catchment (ca. 90 000 inhabitants), is located in the central part of the catchment. The largest wastewater treatment plants discharging purified wastewaters into the Stupia river system are in these three cities.

### 2.2. Sustainability criteria

Sustainability criteria to assess the systems were selected with input from local stakeholders and a literature review of criteria used for

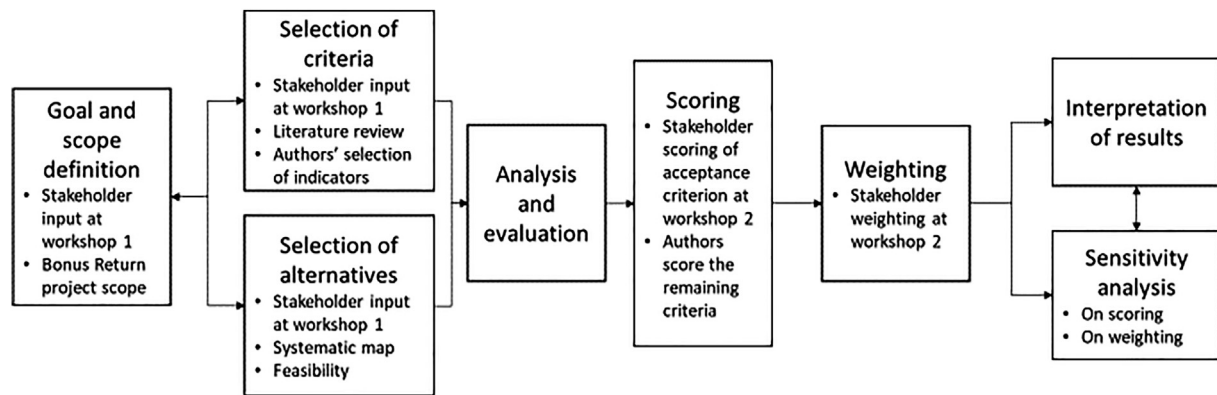


Fig. 1. Process diagram of the methods used, including involvement of stakeholders.

sustainability assessments of wastewater systems. The literature review was performed in order to create a starting point and basis for discussion with stakeholders. The criteria identified in scientific literature are presented in Table 1 in Supplementary Figures and Tables, categorized by the sustainability dimensions: environment, economics, socio-cultural aspects, health and technology.

During the first workshop, stakeholders were first given time to contemplate their priorities based on a default list of sustainability criteria (Table 1 in Supplementary Figures and Tables). They were divided into three groups in which they together came up with a list of maximum 20 criteria and then prioritized between them. In the Fyris workshop, 11 stakeholders participated and in Slupia 22. In both representatives from municipality, wastewater treatment plants, environmental protection groups, farmer's associations and local businesses including were present. Because of large overlaps in the criteria identified and prioritized by stakeholders in both, the same criteria were used for both case-study sites. The sustainability criteria prioritized by the stakeholders and corresponding indicators chosen by the authors are shown in Table 1.

The global warming potential was calculated as the systems net emissions of CO<sub>2</sub> equivalents, i.e. emissions minus CO<sub>2</sub>e offset. The CO<sub>2</sub>e sources within the systems included: transports, wastewater treatment processes, production of heat, production of electricity, production of chemicals, sludge management and sludge spreading. Emissions of methane and nitrous oxide were converted to CO<sub>2</sub>e with the factors 34 and 298, respectively (Huijbregts et al., 2016). Emissions from infrastructure construction were not included. Use of electricity and heat was calculated as the net use, i.e. consumption minus recovery, meaning that the treatment plant used all energy produced on-site. The offset of CO<sub>2</sub>e was calculated as CO<sub>2</sub>e sequestered by sludge application, replacement of

mineral fertilizer with recovered nutrients and replacement of diesel fuel with biogas produced. The energy mix used for Fyris corresponded to emissions of 10.0 tonnes CO<sub>2</sub>-eq/GWh for electricity and 88.6 tonnes CO<sub>2</sub>-eq/GWh for heat (Tumlin et al., 2013). For Slupia, the energy mix corresponded to 300 and 305 tonnes CO<sub>2</sub>-eq/GWh for electricity and heat, respectively, and was calculated based on forecasted energy mix for year 2025 (Polish Investment and Trade Agency, n.d.).

The eutrophication potential was calculated using the CML method (Heijungs et al., 1992) as a worst-case scenario where all nutrient emissions resulted in eutrophication. The emissions considered were P to water, N to water, NO<sub>x</sub> to air and NH<sub>3</sub> to air. For NH<sub>3</sub>, it was assumed all NH<sub>3</sub> turned into dissolved NH<sub>4</sub><sup>+</sup> and therefore the characterization factor for NH<sub>4</sub><sup>+</sup> was used. The characterization factors for P, N, NO<sub>x</sub> and NH<sub>3</sub> used were 3.06, 0.42, 0.13 and 0.33 kg PO<sub>4</sub>e/kg, respectively (Heijungs et al., 1992). Sources of emissions considered were wastewater effluent (N and P), sludge management (NH<sub>3</sub>) and transports (NO<sub>x</sub>). No emissions after fertilizer application were considered. This decision was based on the complexity of the term nutrient use efficiency (Fixen et al., 2015) as well as the lack of evidence on the differences in nutrient emissions after application of recovered nutrients vs application of mineral fertilizer.

The criterion nutrient recovery was based on the mass flow of N and P recovered and returned to agriculture. Total costs included costs for investments of new facilities and for existing infrastructure. Infrastructures included were sewer network, wastewater treatment plants and facilities for sludge storage. Facility for biogas upgrading was not included, neither for costs nor environmental impact. Annual capital cost was calculated with the annuity method (Annuity Method Oxford Reference) using 3% interest and 30–50 years lifetime, depending on the component. The maintenance cost was calculated as 3% of investment costs. The operational costs included costs for electricity, heat, chemicals and staff. Revenues for the nutrient products produced and surplus energy (i.e. recovered that exceeded the systems energy use) were subtracted, resulting in a net cost for the system.

All qualitative criteria were scored by the authors relative to the baseline system using literature, except for the criterion acceptance. The criterion acceptance was assessed qualitatively, with support from the mass flows, as the general acceptance of using the recovered nutrient products as fertilizers in agriculture and was scored by stakeholders at the second workshop. The remaining qualitative criteria were assessed and scored by the authors. The risk of exposure to pollutants was assessed based on the content of heavy metals, pharmaceuticals, microplastics and visible contaminants (e.g. cotton swabs) in the recovered nutrient products. The technical robustness was assessed based on the risk of operational stops and sensitivity to overflows in the system, including the severity of either would occur. The technical flexibility was assessed as the potential to adjust the system according to changes in load or changes in technology.

Table 1

The sustainability criteria used and the indicator for each criterion.

Criterion	Indicator	Quantitative/ qualitative
Global warming potential	Kg CO <sub>2</sub> -eq emitted per cap and year	Quantitative
Eutrophication potential	Kg PO <sub>4</sub> -eq emitted per cap and year (not including recovered N and P)	Quantitative
Nutrient recovery	Kg N and P recovered per cap and year (not including emitted N and P)	Quantitative
Total costs	SEK/PLN per year for investments, O&M and revenues	Quantitative
Acceptance	Acceptance of using recovered nutrient products in agriculture	Qualitative
Risk of exposure to pollutants	Content of pollutants in nutrient products	Qualitative
Technical robustness	Risk for operational stops and overflows	Qualitative
Technical flexibility	Ability to adjust system	Qualitative

### 2.3. Selection of alternatives

The technologies selected for the system alternatives were based on a recent systematic map performed within the BONUS RETURN project (Johannesdottir et al., 2020). The selection of technologies from the systematic map were based on the frequency in the map, stakeholders' preferences, data availability and feasibility. One system alternative in each case was the baseline, representing the current treatment of wastewater in the area. The implementation horizon chosen was until 2025, i.e. seven years from when the assessment was performed, and population in both study sites were determined based on municipal prognoses.

#### 2.3.1. Fyris

The Fyris system alternatives included seven treatment plants in the catchment area and on-site systems. All system alternatives treat wastewater from 249,998 persons connected to the sewer network and 25,000 persons with on-site sewer systems, these numbers include a 14% population increase until 2025. System illustrations can be found in Figs. 1–4 in Supplementary Figures and Tables.

**2.3.1.1. System 0F: Baseline.** The baseline alternative represents the current wastewater management in the area, including seven treatment plants and 10,000 on-site systems. 92% of the inhabitants are connected by sewers to the largest treatment plant, Kungsängsverket. At Kungsängsverket, the wastewater undergoes tertiary treatment. The sludge is anaerobically digested and stored at a central location, after which half of the sludge is returned to agriculture at a mean transport distance of 25 km. At the smaller treatment plants, the wastewater is treated by chemical precipitation and biological treatment. At one smaller treatment plant, the sludge is anaerobically digested on-site. From the other treatment plants, dewatered sludge is transported to Kungsängsverket where it is anaerobically digested. Septic tank contents are transported to Kungsängsverket for co-treatment with sewage. The total reduction during wastewater treatment of N and P in the system is 74% and 95%, respectively.

**2.3.1.2. System 1F: Incineration.** The system and wastewater treatment is the same as in baseline, up until the sludge treatment. Sludge is dried and incinerated at a central plant at a mean transport distance of 15 km. The sludge ash is then processed at a regional facility at a mean transport distance of 100 km for extraction of P. The product is calcium phosphate, which is used as a fertilizer. The total reduction during wastewater treatment of N and P in the system is 74% and 95%, respectively.

**2.3.1.3. System 2F: Nutrient extraction.** At the largest treatment plant, the treatment process is re-designed to facilitate greater resource recovery. The central process of the treatment is anaerobic, in an up-flow anaerobic sludge blanket (UASB) reactor, where biogas is produced. From the effluent water from the reactor, struvite is precipitated and recovered. Next, nitrogen is extracted through ammonia stripping. The sludge produced in the UASB-reactor (which also treats un-digested sludge from smaller treatment plants), is dewatered and stored at a central facility after which 50% is utilized in agriculture. The transport distances are the same as in the baseline system. The total reduction during wastewater treatment of N and P in the system is 88% and 96%, respectively.

**2.3.1.4. System 3F: Source-separation.** The source-separated blackwater is treated as in System 2F: Nutrient extraction. The source-separated greywater and non-separated wastewater is treated as in System 1F: Incineration. Blackwater sludge from the UASB-reactor is used in agriculture. The rest of the sludge produced in the system is incinerated and P is extracted from the ash. It was assumed that all new buildings would have source-separated sewage and it was further assumed that the net

population growth corresponded to new buildings. It was also assumed that when sewers were renovated and renewed, an extra pipe for blackwater would be laid. An ambitious renovation rate of 2% of sewers per year was used. These assumptions resulted in 37% of the residents in the area having source-separated sewage by the year 2025, about one half of which is through sewer renovations and the other through new buildings. The total reduction during wastewater treatment of N and P in the system is 82% and 96%, respectively.

#### 2.3.2. Slupia

Municipal prognoses included no general change in population for the largest municipality in the area, therefore current population size was used. All system alternatives treat wastewater from 206,201 persons connected to sewer networks. Nine wastewater treatment plants were included in the study. No on-site systems were included for the Slupia area due to uncertainties regarding current design and treatment in the area. Incineration of sludge was not included in any of the systems due to the stakeholder's disinterest in the technology. System illustrations can be found in Figs. 5–8 in Supplementary Tables and Figures.

**2.3.2.1. System 0S: Baseline.** In the baseline system, wastewater undergoes tertiary treatment at the largest wastewater treatment plant, Slupsk Waterworks, to which 56% of the inhabitants in the area are connected. The sludge is anaerobically digested and composted. All the composted sludge is then sold as fertilizer and used within a mean transport distance of 13 km. At the smallest treatment plants, wastewater is treated by chemical precipitation and biological treatment. The dewatered sludge is then transported to Slupsk Waterworks for composting and is returned to agriculture too. The total reduction during wastewater treatment of N and P in the system is 86% and 93%, respectively.

**2.3.2.2. System 1S: Reject water.** In this system, the reject water from anaerobic digestion at the largest treatment plant, Slupsk Waterworks, is treated by ammonia stripping. The ammonia sulphate produced is used as a fertilizer. The transport distances are the same as in the baseline system. The total reduction during wastewater treatment of N and P in the system is 87% and 93%, respectively.

**2.3.2.3. System 2S: Nutrient extraction.** The treatment process at the largest treatment plant is the same as in the corresponding system in Fyris (System 2F: Nutrient extraction), except for the sludge management which is described in System 0S: Baseline. The system consists of anaerobic treatment of the wastewater followed by struvite precipitation and ammonia stripping. The total reduction during wastewater treatment of N and P in the system is 92% and 95%, respectively.

**2.3.2.4. System 3S: Source-separation.** This system is largely the same as in Fyris (System 3F: Source-separation), with the exception of the sludge treatment which here constitutes composting instead of incineration. The same assumptions for the fraction of residents in the area with source-separated sewage was made. However, since there was no net population growth in the area based on municipal prognoses, only the sewer renovation led to new source-separated construction. This resulted in only 14% of residents having source-separated sewage by the year 2025. The total reduction during wastewater treatment of N and P in the system is 90% and 94%, respectively.

### 2.4. Analysis and evaluation

#### 2.4.1. Scoring

Scores were given to each criterion on a five-number scale from –2 to 2. Each criterion was scored on the performance relative to the baseline. The baseline system was assigned the score 0 for all criterion. The quantitative criteria were given score based on comparison of the



baseline value of the criterion and the qualitative were based on assessment. Although coarse, the score was considered sufficient for the aim and level of detail in this study. The scoring was based on the following:

- Over 40% better than baseline: score 2
- Up to 40% better than baseline: score 1
- Within 20% of baseline: score 0
- Up to 40% worse than baseline: score -1
- Over 40% worse than baseline: score -2

#### 2.4.2. Weighting

The stakeholders at each workshop weighted the criteria in groups by distributing 100 units between the criteria based on their own prioritization. The average weights assigned by the groups were used for calculating the sustainability score. At the workshop in Fyris, seven stakeholders attended representing municipality, consultants and farmers. At the Slupia workshop, 14 stakeholders participated.

#### 2.4.3. Interpretation of results

The performance of the different systems on the selected criteria were aggregated into a sustainability score. The sustainability score was calculated with the weighted sum method according to equation (1)

$$\text{Total score} = \sum_{i=1}^n \text{weight}_i \times \text{score}_i \quad (1)$$

where the weight is decided by the local stakeholders and the score is based on the systems' performance on the criterion in question. The sustainability score of the systems were then compared in reference to the baseline, which was assigned the sustainability score 0.

#### 2.5. Sensitivity analysis

For the qualitative criteria, like for the quantitative, the evaluation was done with the focus on the overall systems performance and the effects on catchment level. To test the robustness of the resulting sustainability scores, i.e. what systems are most sustainable in each local context, two sets of sensitivity analyses were performed. The first was done by changing the scores of the individual criteria. The sensitivity of the qualitative criteria was done by changing the score of each criterion by 1 and evaluating the overall sustainability score whilst using the average weights assigned to the criteria. The change of score of 1 corresponds to a change in the performance of 20%. For the quantitative criteria, the performance of each criterion was changed by 20% and the overall sustainability score was evaluated whilst using the average weights assigned to the criteria. The second sensitivity analysis was based on the weighting. The maximum and minimum score for each system was calculated by using the set of weights assigned to the criteria by the individual stakeholders.

**Table 2**

The emissions of CO<sub>2</sub>e and PO<sub>4</sub>e in kg/cap,yr, the amounts of N and P recovered in kg/cap,yr and the total costs in SEK/cap,yr or PLN/cap,yr for all systems.

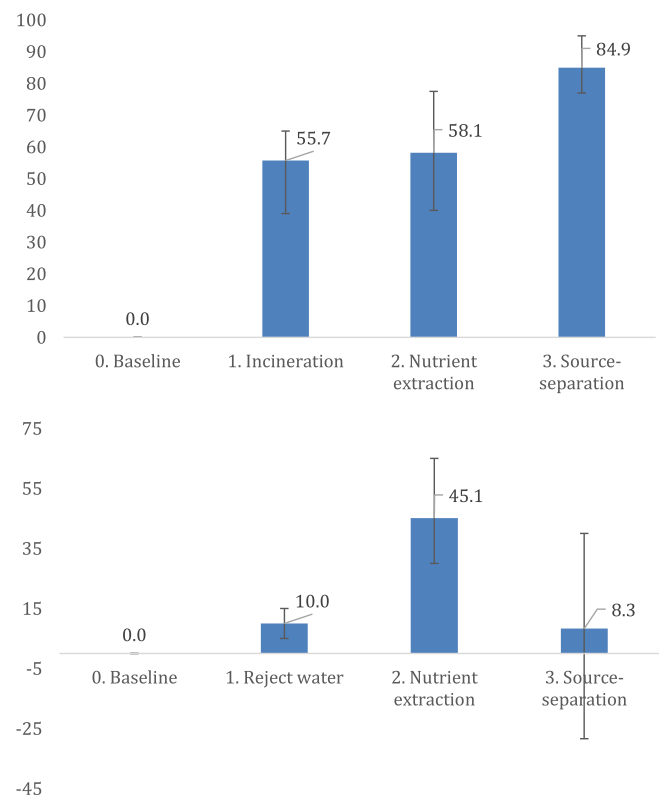
System	Global warming potential (kg CO <sub>2</sub> e/cap,yr)	Eutrophication potential (kg PO <sub>4</sub> e/cap,yr)	Nitrogen recovered (kg N/cap,yr)	Phosphorus recovered (kg P/cap,yr)	Annual cost (SEK or PLN/cap,yr)
System 0F: Baseline	19.8	0.67	0.022	0.25	1,814
System 1F: Incineration	20.0	0.68	0	0.46	1,821
System 2F: Nutrient extraction	12.7	0.36	3.6	0.14	1,937
System 3F: Source-separation	17.4	0.48	1.4	0.48	2,029
System 0S: Baseline	36.2	0.49	0.14	0.5	356
System 1S: Reject water	35.7	0.48	0.41	0.5	365
System 2S: Nutrient extraction	39.6	0.31	2.44	0.6	403
System 3S: Source-separation	36.4	0.38	0.87	0.51	479

### 3. Results and discussion

#### 3.1. Quantitative criteria

The values of the quantitative criteria for both case-studies are presented in Table 2. A detailed presentation of CO<sub>2</sub>e emissions for Fyris is presented in Fig. 9 and for Slupia in Fig. 10 in Supplementary Figures and Tables.

For the Slupia case, most systems had similar net emission of CO<sub>2</sub>e, with System 2S: Nutrient extraction having the highest (Table 2). This is partly due to the large fraction of emissions originating from energy production in all systems (Fig. 2 in Supplementary Figures and Tables). In all systems, both Fyris and Slupia, except for System 2F: Nutrient extraction, the largest source of CO<sub>2</sub>e emissions was from the wastewater and sludge treatment (Figs. 1 and 2 in Supplementary Figures and



**Fig. 2.** Sustainability scores for each system relative to the baseline in Fyris (upper) and Slupia (lower). The error bars show the sustainability scores when using the set of weights assigned by the individual stakeholders (i.e. sensitivity analysis).

Tables). For System 2F: Nutrient extraction, the largest contributor was production of chemicals, as the chemical use was high in this system. While the chemical use in the corresponding system 2S in Slupia was high also, the largest contributor of CO<sub>2</sub>e emissions was the wastewater treatment process followed by heat production. The Systems 2F and 2S also have high demand on heat and are the most resource-exhaustive systems but also the ones with highest offsets of CO<sub>2</sub>e by replacing mineral fertilizers with recovered nutrients.

The eutrophication potential was lowest in the System 2: Nutrient extraction in both case-studies, corresponding to the systems with the highest nutrient recovery. In these systems, nutrients were extracted into products instead of being emitted as potentially eutrophying emissions. Note that the emissions resulting from application of fertilizer (sludge, compost or other recovered nutrient product considered) is not included in the assessment.

In Fyris, the systems 2F: Nutrient extraction and 3F: Source-separation had lower net CO<sub>2</sub>e emissions, mostly due to larger offsets resulting from higher nutrient recovery (Fig. 1 Supplementary Figures and Tables). The Systems 2 and 3 (both case-studies) include the same constellation of technologies, namely anaerobic treatment as central treatment process and nutrient extraction by struvite precipitation and ammonia stripping. The main difference is that in the Systems 3F and 3S, this innovative treatment process is applied to the source-separated blackwater only. In these systems, some of the negative aspects like high chemical and heat demand of these technologies is therefore reduced by treating a smaller amount of waste, i.e. only blackwater from households with source separation (37% and 14% for Fyris and Slupia, respectively) compared to the mixed wastewater from all households. At the same time, the nutrient recovery is relatively high still because the blackwater fraction contains most of the nutrients in wastewater. However, since the fraction of wastewater which is source-separated in the Slupia case is so low the benefits of the system become small compared to the negative aspects such as costs.

For both case-studies, the costs associated with the systems increased with increasing complexity and scale of interventions. Worth noting is the small difference between baseline and 1F: Incineration in the Fyris case. Despite the inclusion of incineration plant and ash processing facility, when considering the entire wastewater management system in the catchment, the additional cost per capita for the 1F: Incineration system is not very high.

### 3.2. Qualitative criteria

For the criterion *Risk of exposure to pollutants*, the nutrient products and residuals were used for evaluation. Table 3 shows the types and amounts of nutrient products in each system in both case-studies. Because of similarities in the systems between the Slupia and Fyris cases, the reasoning behind evaluation of qualitative criteria are similar. For Slupia, the *Risk of exposure to pollutants* was assumed to be the same compared to the baseline as in Fyris.

Struvite can contain heavy metals that are incorporated into the struvite crystals during precipitation (Rahman et al., 2014) as well as pharmaceuticals adsorbed (Harder et al., 2019). The content of both is probably lower than in both conventional sludge (Rahman et al., 2014)

and nutrients recovered from sewage sludge ash (Harder et al., 2019). Calcium phosphate was assumed to be free of pharmaceuticals, visible contaminants and microplastics due to the preceding incineration but potentially containing heavy metals, although not more than conventional sludge. Blackwater sludge was assumed to contain all pollutants considered but in lower amounts than in conventional sludge, except for pharmaceuticals (Harder et al., 2019). Ammonium sulphate was assumed to not contain any of the considered pollutants. Based on these assumptions, the baseline and System 2F: Nutrient extraction were considered to have the highest risk of causing exposure to pollutants, due to the high amounts of both conventional sludge and were assigned the score 0. The System 1F: Incineration was assigned the highest score, 2, due to the absence of conventional sludge. The System 3F: Source-separation was assigned the score 1.

System 1F: Incineration was considered to have the same technical robustness as the baseline, as the only additions to the systems were mono-incineration and ash-processing to extract P. The System 2F: Nutrient extraction was considered as less robust, due to the sensitive treatment processes of anaerobic treatment of raw wastewater (Kjerstad 2017), and chemical-intensive processes of struvite precipitation and ammonia stripping. Therefore, the System 2F: Nutrient extraction was assigned score -2. System 3F: Source-separation includes the same treatment as in System 2F: Nutrient extraction, but only for the blackwater fraction which could make the process more stable (Kjerstad 2017), and only 37% of wastewater is source-separated. Therefore, the consequences of lower robustness are less important in this system. Instead, source-separation can increase robustness in the system since the risk of and consequences of overflows are lower if the blackwater is managed separately. Therefore, System 3F: Source-separation was assigned score 1.

For all systems, the flexibility was considered higher than baseline, so they were all assigned score 1. Worth noting is the assumption on the system 1F: Incineration, which includes construction of a facility for P recovery from ashes, that is based on the large interest in this and likelihood of it being a technology soon implemented in full-scale in northern Europe.

In the System 3S: Source-separation, the fraction of source-separated wastewater was only 14%. Because of the small difference from the baseline system, the robustness and flexibility were assumed to be the same, i.e. score 0. For System 2S: Nutrient extraction however, which is in principle the same as in the Fyris case, the same scores were assigned, i.e. -2 for robustness and 1 for flexibility. Flexibility and robustness of System 1S: Reject water was assumed to be like the baseline.

### 3.3. Sustainability scores

The score for each criterion, average weight assigned to each criterion by the local stakeholders at the second workshop and the sustainability score for each system for the Fyris case-study is presented in Table 4 and for the Slupia case in Table 5.

The resulting sustainability scores shown in Tables 4 and 5 are illustrated in Fig. 2. The sustainability scores for the Fyris cases compared to its baseline was generally higher than corresponding scores for Slupia. This indicates that the perceived benefits of the innovative systems are

**Table 3**

The types and amounts of nutrients products for fertilizer use in each system for both case-studies.

Nutrient product	System 0: Baseline		System 1: Reject water/Incineration		System 2: Nutrient extraction		System 3: Source-separation	
	Slupia	Fyris	Slupia	Fyris	Slupia	Fyris	Slupia	Fyris
Conventional sludge (kg dry matter/yr.cap)		5.83			5.67			
Blackwater sludge (kg dry matter/yr.cap)							2.91	1.42
Composted sludge (kg dry matter/yr.cap)	38.4		38.4		38.2			0.0
Struvite (kg P/yr.cap)					0.318	0.484	0.0533	0.140
Ammonium sulphate (kg N/yr.cap)			0.279		2.18	3.29	0.746	1.29
Calcium phosphate (kg P/yr.cap)				0.455				0.327

**Table 4**

The score for each criterion and total sustainability score for each system for Fyris and the average weight assigned to each criterion by stakeholders. The range of weights assigned to each criterion by the stakeholders are given in parenthesis.

Criterion	System 0F: Baseline	System 1F: Incineration	System 2F: Nutrient extraction	System 3F: Source-separation	Average weight (n = 7)
Global warming potential	0	0	1	0	10.4 (7.5–20)
Eutrophication potential	0	0	2	1	5.6 (0–10)
Nutrient recovery	0	2	2	2	12.5 (7–20)
Total costs	0	0	0	0	17.1 (10–20)
Acceptance	0	0	1	1	23.6 (10–40)
Risk of exposure to pollutants	0	2	0	1	10.7 (5–20)
Technical robustness	0	0	–2	1	10.7 (5–15)
Technical flexibility	0	1	1	1	9.3 (5–15)
<b>Total score</b>	<b>0</b>	<b>55.7</b>	<b>58.1</b>	<b>84.9</b>	

**Table 5**

The score for each criterion and total sustainability score for each system for Slupia and the average weight assigned to each criterion by stakeholders. The range of weights assigned to each criterion by the stakeholders are given in parenthesis.

Criterion	Baseline	System 1S: Reject water	System 2S: Nutrient extraction	System 3S: Source-separation	Average weight (n = 14)
Global warming potential	0	0	0	0	9.2 (5–15)
Eutrophication potential	0	0	1	1	13.3 (5–30)
Nutrient recovery	0	1	2	2	10.0 (5–15)
Total costs	0	0	0	–1	19.5 (5–30)
Acceptance	0	0	0	–2	13.0 (10–40)
Risk of exposure to pollutants	0	0	1	1	20.5 (15–40)
Technical robustness	0	0	–2	0	7.8 (5–10)
Technical flexibility	0	0	1	0	6.8 (5–10)
<b>Total score</b>	<b>0</b>	<b>10.0</b>	<b>45.1</b>	<b>8.3</b>	

comparatively higher in Fyris in relation to the respective baseline.

In Fyris, the System 3F: Source-separation obtained the highest sustainability score, while in Slupia it got the lowest (Fig. 2). This could be due to the fraction of households with source-separation being much higher in the System 3F: Source-separation than in System 3S: Source-separation. Additionally, the acceptance for the System 3S: Source-separation was low among the local stakeholders in Slupia whilst in Fyris the acceptance for source-separation was higher. Stakeholders in Slupia justified the low acceptance with the source-separation system being expensive and complicated without producing more attractive nutrient products than the other systems.

### 3.4. Sensitivity analysis

The results of the sensitivity analysis based on the weighting of criteria is illustrated with the error bars in Fig. 2. For both case-studies, the different sets of weights assigned by the stakeholders could affect the results on what system is the most sustainable. The sensitivity analysis revealed that the order changed from System 2F: Nutrient extraction having the second highest score, to having the lowest score compared to the baseline whilst the System 3F: Source-separation always receives the highest score when varying individual criteria performance by 20%. In none of the sensitivity analyses made did any system perform worse than the baseline for Fyris. This means that all systems considered are more sustainable than the baseline and that the source-separation system is the most preferable alternative, although marginally depending on the stakeholder weighting.

For the Slupia case, sensitivity analysis revealed that changing the individual criteria performance by 20% could change the order of sustainability scores from System 1S having the second highest score, to having the lowest score compared to the baseline (Table 3 Supplementary Figures and Tables). Considering the scoring, the analysis supports that the System 2S: Nutrient extraction is the most sustainable one. Based on the stakeholder weighting though, source-separation could be equally sustainable. But it could also result in System 1S: Reject water and 3S: Source-separation being less sustainable than the baseline. This means that the System 3S: Source-separation and 1S: Reject water could potentially be less sustainable than the current wastewater management, as represented by the baseline system.

### 3.5. Discussion

The scenarios considered in this paper encompassed circular solutions for recycling nutrients which are all technically ready. Despite their effectiveness in reducing and reusing nutrients, there is a broad spectrum of factors beyond technical aspects that need to be accounted for when exploring new system solutions and non-technical aspects can very often play a decisive role for whether solutions are implemented and supported (Barquet et al., 2020). Results from this study reflects this in the different weights that stakeholders assigned to the same criteria in each of the cases (Tables 4 and 5). Additionally, in neither Slupia nor Fyris, technical readiness was weighted highest by the stakeholders.

Negative sustainability scores were obtained in some instances of the sensitivity analysis, for example when increasing the eutrophication potential for System 3S: Source-separation in Slupia. This shows the need for sustainability assessment of interventions, as certain conditions could potentially lead to the interventions not being more sustainable options at all. This is an important aspect to include in the decision-making process and something which a sustainability assessment such as presented in this study can provide. This study further confirms the benefits of enhancing the resource recovery from wastewater as pointed out by for example Trimmer et al. (2017). Additionally, the potential reduction in eutrophication of the two systems System 3F: Source-separation in Fyris and System 2S: Nutrient extraction in Slupia was supported by a recent study (Koskiahio et al., 2020).

Whilst in this paper the qualitative criteria have been defined as objectively as possible and based on literature and expert knowledge, these criteria are heavily dependent on values and perceptions (Barquet et al., 2020). Acceptance, which in this paper is connected to the use of recovered nutrients in agriculture, faces various constraints including the lack of user-friendly applications and competitiveness against standard products on the market (Barquet et al., 2020). However, several stakeholders at the last workshops were in fact considering the acceptance of the entire system rather than only that of the recovered products. Risk of exposure to pollutants is far more complex than estimating the relative content of pollutants in different recovered products, as was performed in this paper. It is, however, meaningful to include an estimation of the pollution risk in a comparative assessment of nutrient recovery technologies.

Recovering nutrients from human excreta is subject to a complex set of policies, regulations and varying public acceptance. The market for recovered nutrient products is still emerging and coupled with uncertainties (Barquet et al., 2020). In both case-studies, the current means of returning nutrients to agriculture is by utilizing the sludge. The acceptance of the compost product in Stupia is high locally. In Fyris, only half of the sludge is returned to agriculture. The debate in Sweden on whether recycled sludge and nutrients should be used in food production remains polarized and value-driven (Dagerskog et al., 2020) and there is currently an investigation on national level on banning, partially or completely, the use of sludge on arable land (Government Offices of Sweden 2018). Although the legislative landscape in wastewater and sludge management is presently uncertain, performing studies such as this contributes to the scientific body of evidence on sustainability of circular technologies.

## 5. Conclusions

The sustainability assessment showed that re-design of the wastewater treatment was the most sustainable intervention in both Fyris and Stupia. Despite the large resource consumption of the systems where wastewater treatment was re-designed to consist of anaerobic treatment, struvite precipitation and ammonia stripping, the benefits were greater. This shows that a large change to the current system can be a sustainable option when assessing the whole system, including production of fertilizers. Furthermore, this study further confirms the benefits of enhancing resource recovery in wastewater management.

Introduction of source-separation received high overall sustainability score in Fyris. In Stupia however, where source-separation was implemented in 14% of households compared to 37% in Fyris, the source-separation system received a low score. This shows that source-separation needs to be implemented for a significant fraction of households for the benefits to outweigh the costs of implementation.

## CRediT authorship contribution statement

**Solveig L. Johannesdottir:** Data curation, Formal analysis, Conceptualization, Writing – original draft, Visualization. **Erik Kärrman:** Methodology, Conceptualization, Writing – review & editing. **Karina Barquet:** Resources, Writing – review & editing, Project administration, Funding acquisition. **Jari Koskiahho:** Resources, Writing – review & editing. **Olle Olsson:** Data curation, Resources, Writing – review & editing. **Marek Gielczewski:** Data curation, Resources, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cesys.2021.100030>.

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